CHARACTERISTICS OF CORAL
AND CORAL DREDGING

by

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Ocean Engineering Program

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ABSTRACT

This report was prepared to fill the information gap for civil engineers involved with the dredging of coral and its use as construction material. Eighteen kinds of coral are discussed and illustrated in terms of engineering properties, excavation data, coral reef formation and world-wide distribution.

PREFACE

This investigation was conducted as part of the continuing research program at the Center for Dredging Studies, Texas A&M University, and was partially supported by the Sea Grant College Program and by the Center for Dredging Studies at Texas A&M University.

Research was performed by B.R. Schlapak in association with Dr. John B. Herbich, Director of the Center for Dredging Studies.

Technical editing by Dr. Gisela Mahoney of the Sea Grant College Program is deeply appreciated. The manuscript was typed for publication by Ms. Rita Halsell.

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INTRODUCTION

This study was generated by the need for construction materials in Micronesia and nearby areas. Coral, which is extracted by dredging, appeared to be the only construction material available locally.

Despite much work done with coral during World War II, there appeared to be few reports on the engineering properties of this remarkable organic rock. Local information was accessible only at the libraries of The Engineer School, Fort Belvoir, Virginia, and North Carolina State University, Raleigh. This report was prepared to fill the existing information gap for civil engineers involved with the dredging of coral and its use as construction material.

CORAL REEF FORMATION

According to Legget[8], coral, one of the most widespread building materials in the Pacific area, is a material that was generally regarded as suitable only for specialized work until the Second World War. Coral, before the end of the war, became well known as the "Pacific Lifesaver". There are many types of this organically formed rock but that most useful as aggregate occurs in reefs and ledges, and has characteristics similar to those of soft limestone[1].

Coral is remarkably different from other rocks because it is made by the combination of several thousands of lime-secreting invertebrate marine animals (Anthozoans) and millipore algae plants (Thallophytes) (Figure 1). Coral is the generic name for biogenic carbonate rocks made by marine animals and plants which secrete calcareous skeletons. The exact process of algae calcification and the mechanics of calcium carbonate deposition in marine invertebrates are not known. It is also not known whether calcium is taken directly from seawater or from the food (plankton and nekton) eaten by the animals[2].

Coral limestone reef structures are made by thousands of different kinds of lime-secreting invertebrates in combination with milipore calcareous algae plants (seaweeds) (Figure 2). The animals have individual polyps which rise and grow by budding. The animals and plants live in symbiotic and commensal relationships. They secrete an elaborate, rigid limestone latticework which is highly porous, brittle and easily broken when in the fresh state. The surface of the latticework is composed of an infinite number of cells, pores, sharp edges and rock filigree that

Figure 1. Closeup View of an Oceanside Coral Head.

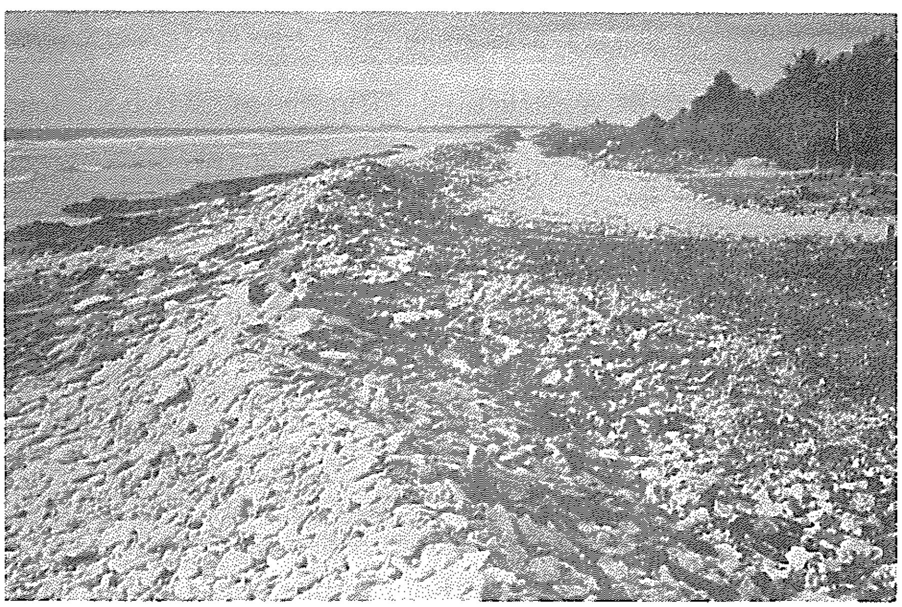

Figure 2. Windward Side of the Reef at Jaluit Atoll, Marshall Islands.

are created by the animals and plants as they grow and develop. Two types of plants are important contributors to limestone reefs. Coralline red algae (porolithon) develop very dense, compact limestone with microscopic cells. These red algae form a hard, wave-resistant rock and give the reef edge a characteristic red-brown color. Fragments of red algae also make up a large number of the angular pieces of coral limestone breccia. Algae grow over the surface of the more delicate corals and loose sediments, cementing the mass into a stronger and more rigid structure. The second important plant contributing to limestone reef development is the calcareous green algae (Halimeda). Green algae do not form solid rock like red algae but instead produce large quantities of flakes (sand to silt sizes) of calcareous soft material which form the bulk of fine-grained material found in marine sediments. As the bush coral-algae network expands and builds upward the outward, older polyps die and gradually the dead base is buried by the growth of other animals and by the abundant rock debris that storm waves break from the living parts[3]. When the coral polyp (inhabitant of the shell) dies, the skeleton fills with water and this water gradually becomes a saturated solution of calcium carbonate. If the old polyp shell happens to fill with fine grains of sand, these grains are cemented together. In the absence of sand, deposits of calcium carbonate form. Sometimes the water deepens and pressure hardens the material while dissolving the softer parts, thus leaving many holes and crevices[4]. The principal constituents of limestone deposits are amorphous calcium carbonate, chitin, nacre and the minerals calcite and aragonite[5].

Because the precipitation of calcium carbonate requires conditions of high carbon dioxide solubility and low ionic strength, a shallow, warm, saline environment or medium breeds corals. Thus coral reefs are adapted only to warm oceans as is shown in Figure 18. Consequently, coral reefs are common in many areas in the South Pacific, Indian Ocean, Red Sea and Gulf of Mexico. Most prominent is the reef of northern Australia. Fringing and barrier reefs are found around many volcanic islands and some 330 coral atolls dot the tropical oceans. Corals live in relatively shallow water, some can be found at depths down to 250 feet (Figures 3-7).

Darwin's explanation of coral reef formation, although debated for the better part of a century, is now accepted and confirmed by the discovery of basalt at Eniwetok Atoll at depths of minus 4158 and 4610 feet as well as minus 560 feet in Bermuda[6]. Darwin published his subsidence theory in 1842. He felt that in recent times the islands in warm waters had been slowly sinking relative to sea level and the coral reefs had grown upward and outward. Thus a volcanic island in warm waters started with a fringing reef which became a barrier reef and eventually became an atoll. This theory was attacked for many years and many other theories were offered. Davis, in his 1914 trip and 1928 book on the coral reef controversy, supported the Darwin theory principally because of a consistent lack of detritus in the valleys of the volcanic islands[7].

Contrary to general belief, coral reef islets are formed as a result of storms rather than built by live corals. On every reef the volume of live coral is a small fraction of the mass of the reef, a thin veneer of life coating a vast bulk of dead coral debris. The lateral and vertical spread of a coral colony is determined by environmental factors. Mean tide is the limit of upward growth but the upward increment of the reef itself is independent of organic factors; it is the result of manipulation

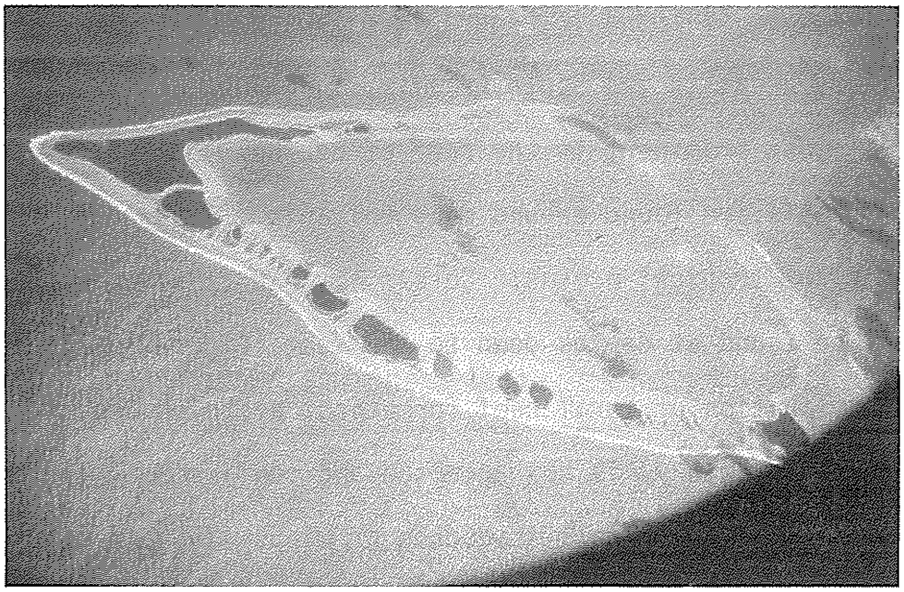

Figure 3. Aerial View of Ujelang Atoll, Marshall Islands.

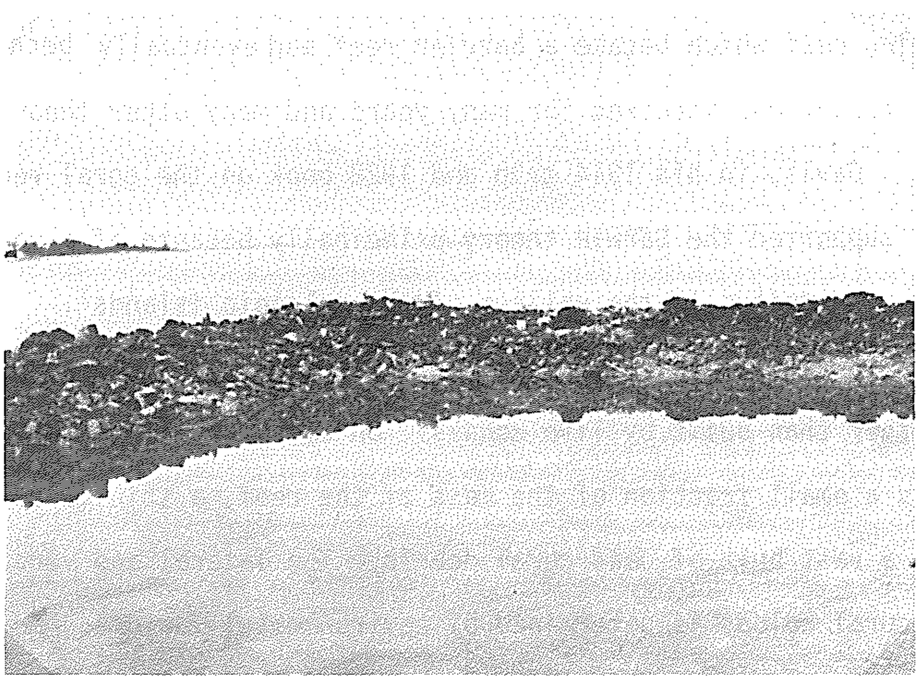

Figure 4. The Other Side of the Lagoon, 10 Miles Away, As Seen From Jabor, Jaluit Atoll, Marshall Islands.

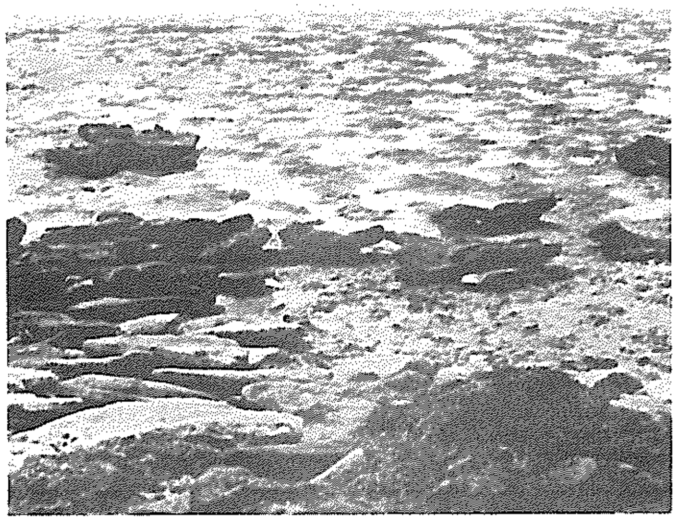

Figure 5. Windward, Oceanside of Reef at Jaluit Atoll, Low Tide

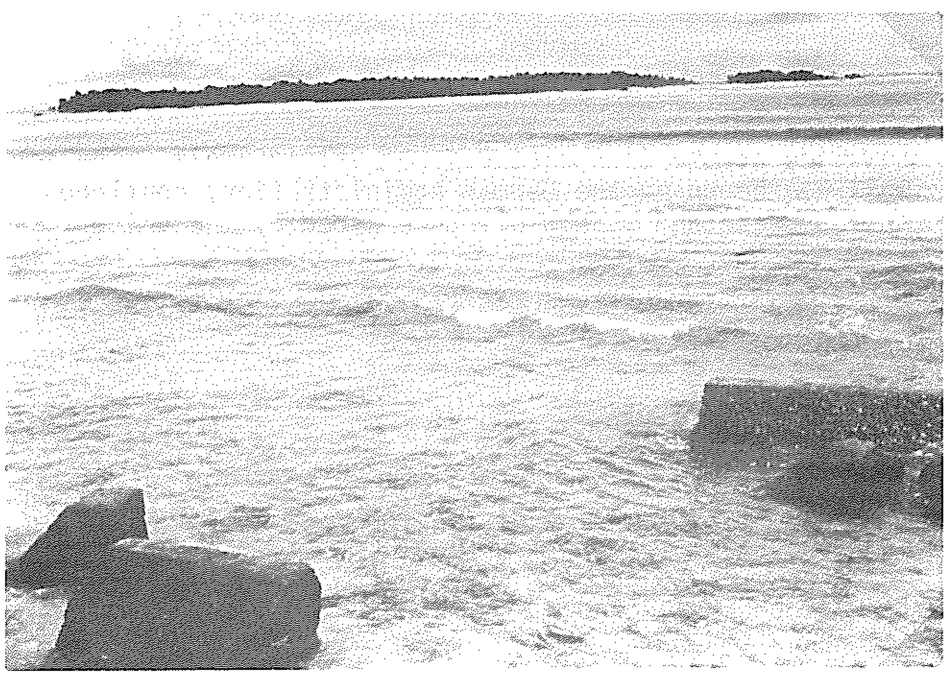

Figure 6. Southeast Pass Through the Reef, Jaluit Atoll, Marshall Islands.

Figure 7. Low Tide at the Southeast Pass of Jaluit Atoll. The sea wall was begun by the German administration, continued by the Japanese and is now being repaired by the United States.

of coralline material by waves and winds. The prodigious momentum of storm waves, magnified by hydraulic pressure in the irregular cracks and crevices of rough coral, rips chunks of growing coral away from the reef. With these tools, constantly diminished in size by attrition, violent waters wreak havoc among other corals. Strong waves carry fragments out into flanking depths, and as the storm wanes weaker waves deposit their burden of coarse fragments on top of the reef[8].

Adjacent to a reef the water may be saturated with calcium carbonate. Significant waves such as combers can change hydrostatic pressure and aerate certain zones of water. This action may reduce the amount of carbon dioxide held in solution. Thus, the chemical equilibrium changes so that calcium carbonate precipitates and cements loose fragments into the reef. In addition to inorganic precipitate, metabolic processes of microorganisms contribute additional lime cement. As time passes, waters over the reef become shallower and eventually a passing storm may heap a few coral boulders above tide. The virgin islet left by one storm may be partially removed by another storm and rebuilt yet higher by a third storm. The birth of an islet surmounting a barrier or atoll reef seems to be quite a whim of nature[9].

A coral islet is an effective breakwater and currents sweeping around it deposit their load of sediment in quieter waters near its ends. The net effect is to extend the end of the islet in the direction of the prevailing air and water currents. The most rapid construction of the reef and the islets which eventually surmount it takes place on the segment nearest the full force of prevailing wind and water currents. This is indicated by the presence of the largest islets on the weather side of an atoll or barrier reef. Smaller islets are found on the other portions of a reef. (It is this regularity which has given rise to the axiom that an entrance to the lagoon of an atoll or barrier reef is to be found on the lee of the reef.) All forms of life on atolls or barriers are immigrant forms[10].

In open ocean waters, isolated pinnacles of heads of coral rise to shallow depths. Such clumps are too small to have been charted but many are massive enough to rip the bottom out of a ship. The great majority of these are probably within lagoons or near known reefs. The idea that corals grow with the rapidity of mushrooms and that waters which were safe last year may be of lethally shallow depth this year is ridiculous.

Corals and reefs built of their debris are also features of ancient geological formations. What is now high and dry was once the floor of a shallow sea. Marine sediments that are now lithified and elevated frequently enclose limestone masses that were once coral reefs. Guadalupe Peak in west Texas is the southwest terminus of a horseshoe-shaped reef. This fossilized reef is highly porous and is a reservoir of petroleum[11].

Several drawings and maps follow which illustrate the character of reefs (Figures 8-17).

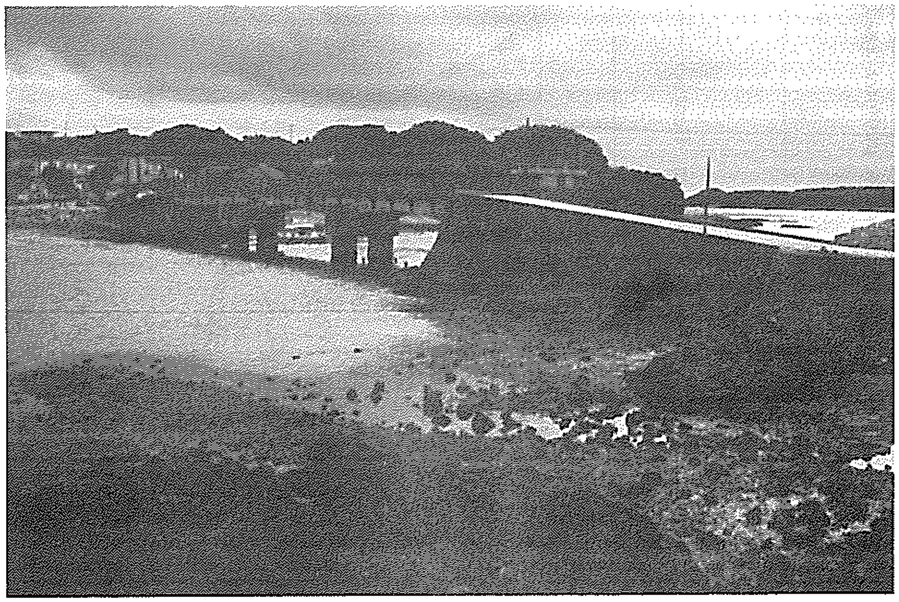

Figure 8. Part of the Fringing Reef of Okinawa. Lithified deposits of coralline limestone exist to elevations of 100-200 meters. The reef is not flourishing.

Figure 9. Leeward Side of Luzon, Philippines. Only a few coralheads visible.

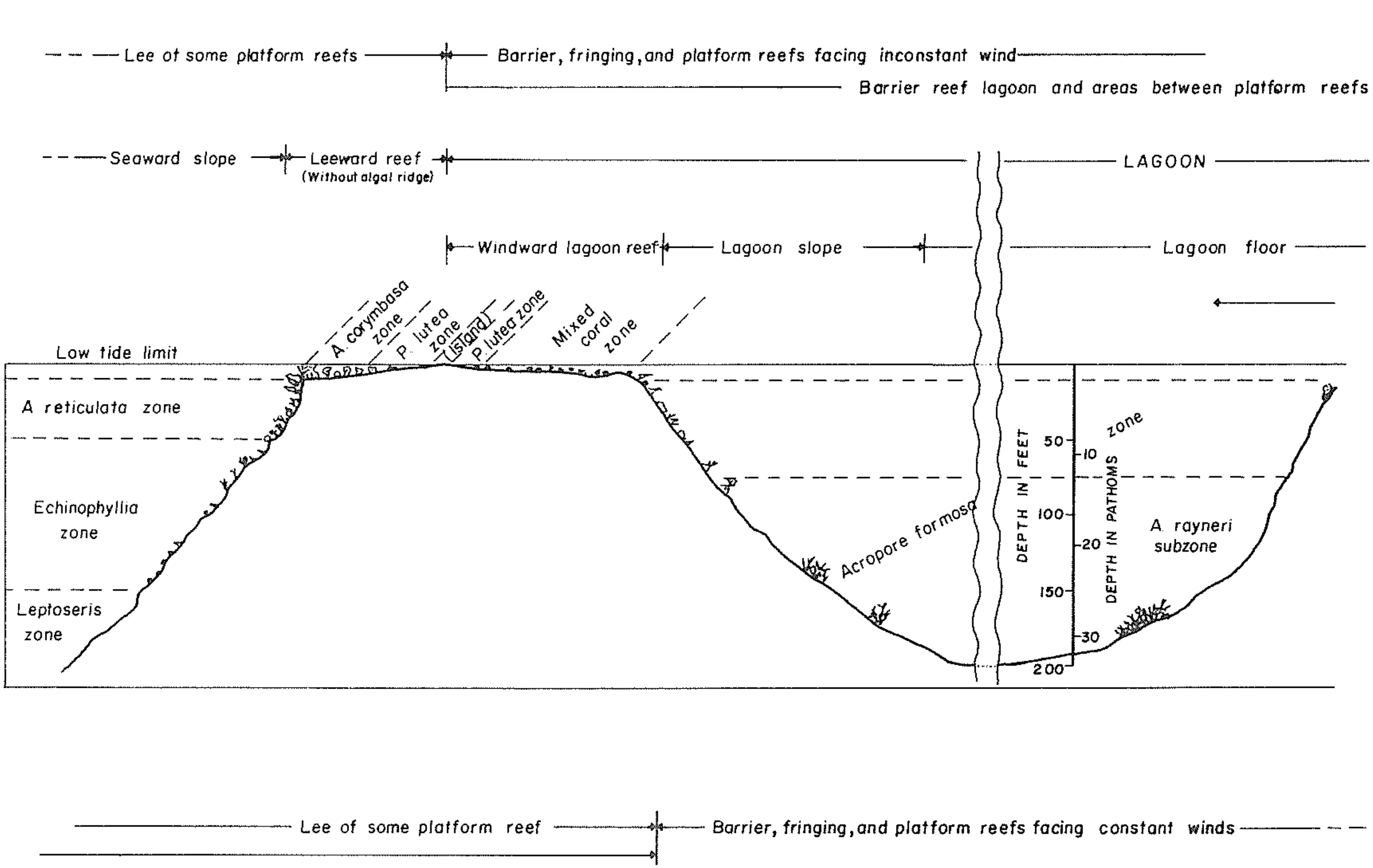

Figure 10. Cross-Section of a Barrier Reef. After Wells, GSA, 1957.

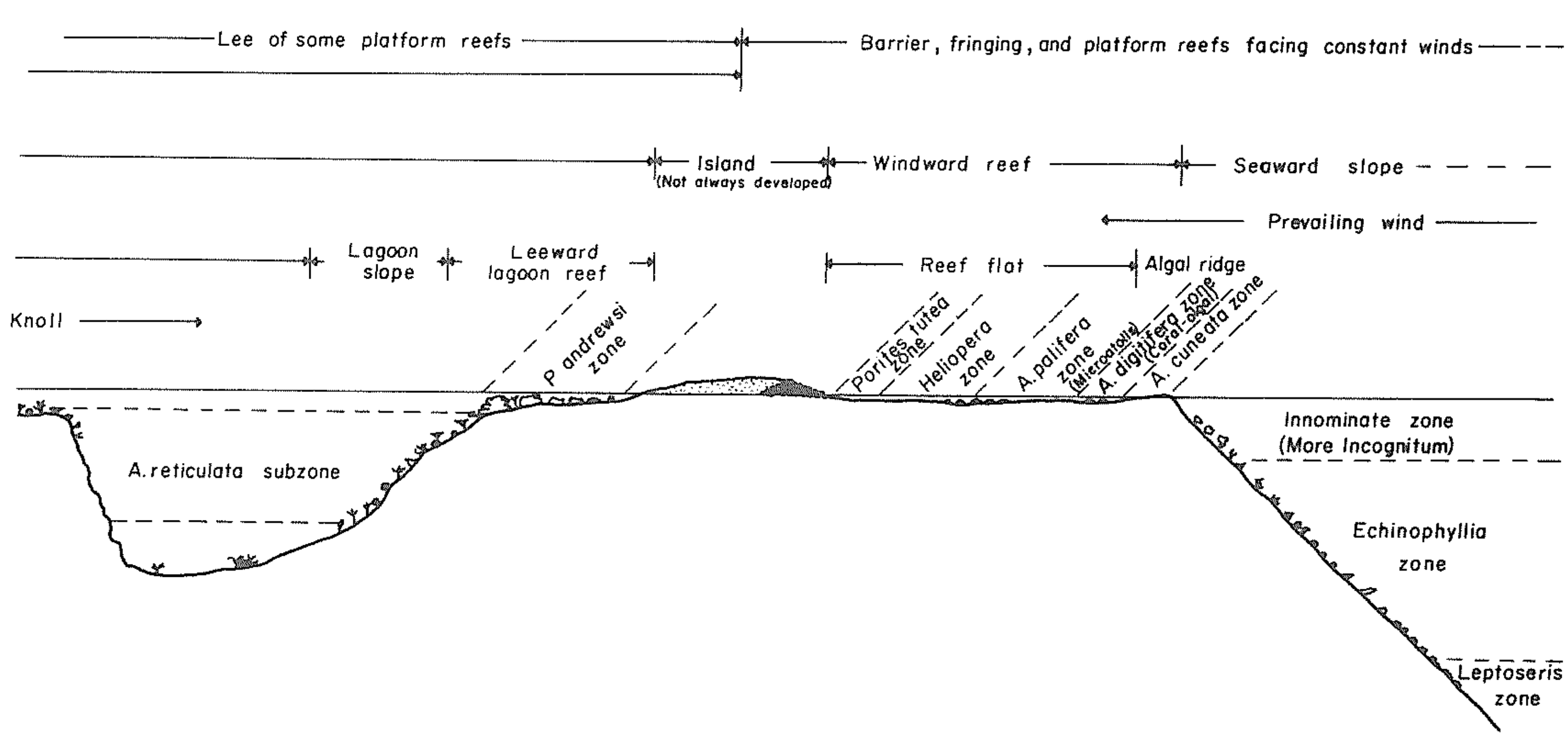

Figure 11. Cross-Section of an Atoll. After Wells, GSA, 1957
(vertical exaggeration - 6 times)

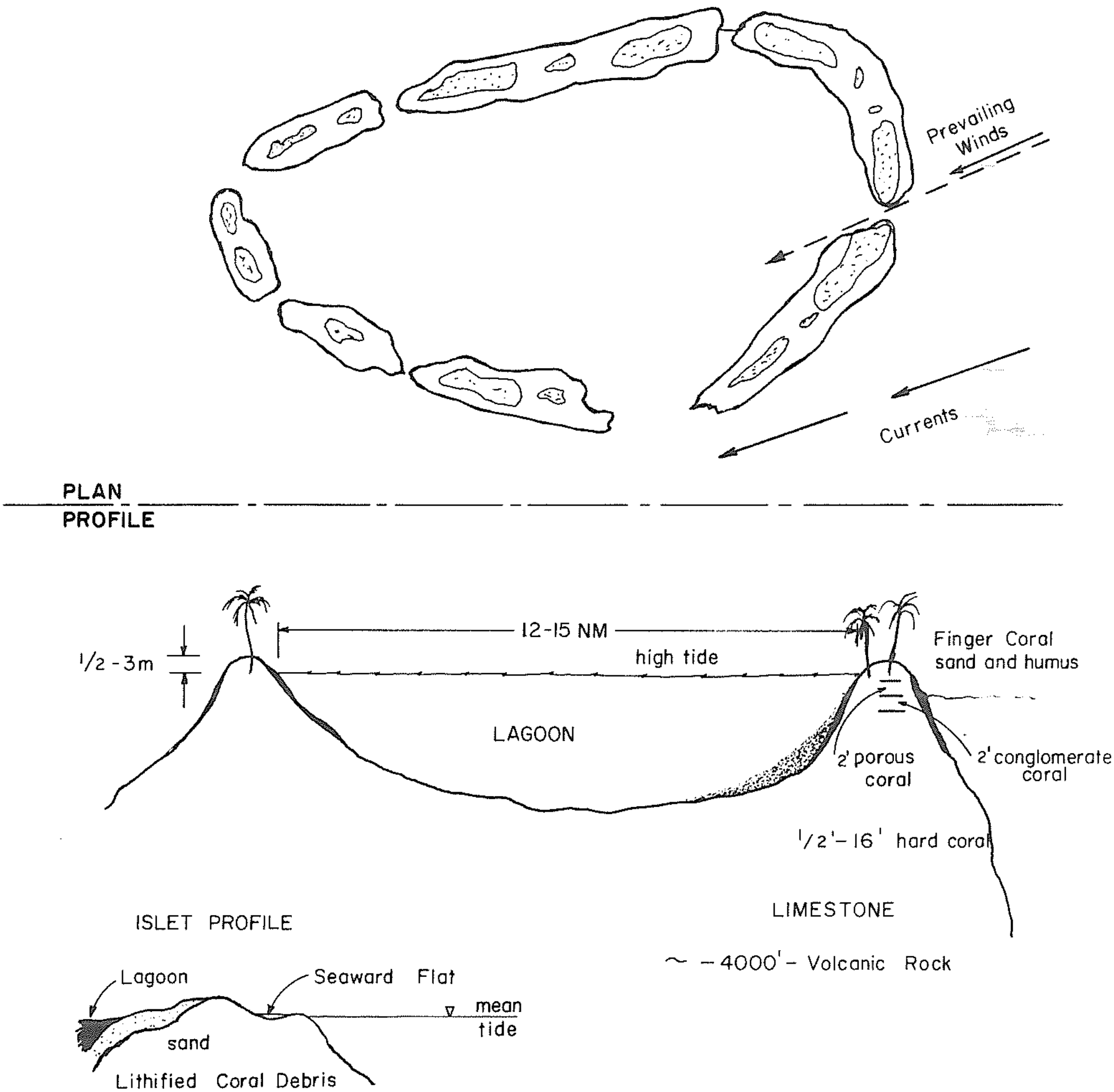

Figure 12. Typical Pacific Atoll.

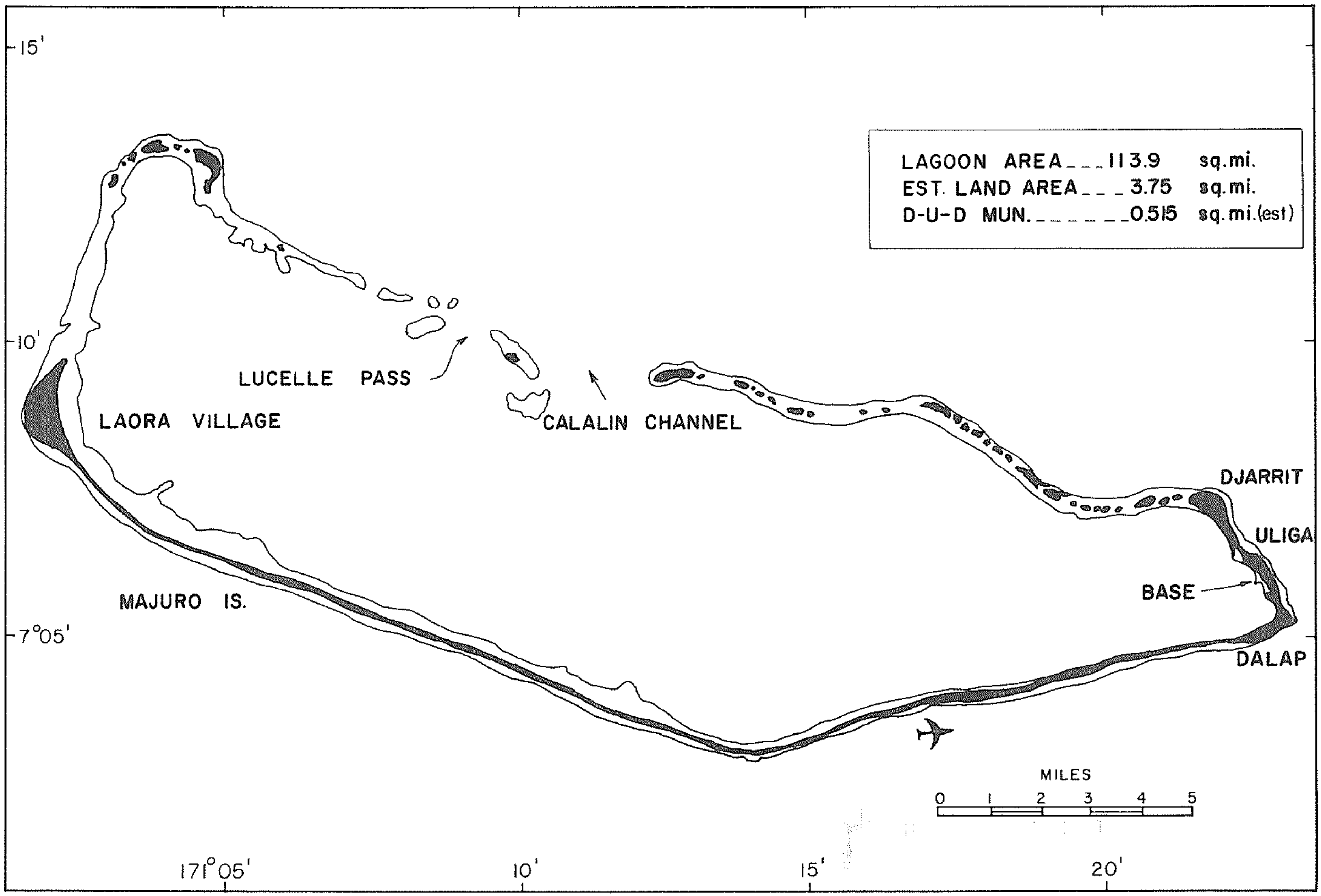

Figure 13. Majuro Atoll.

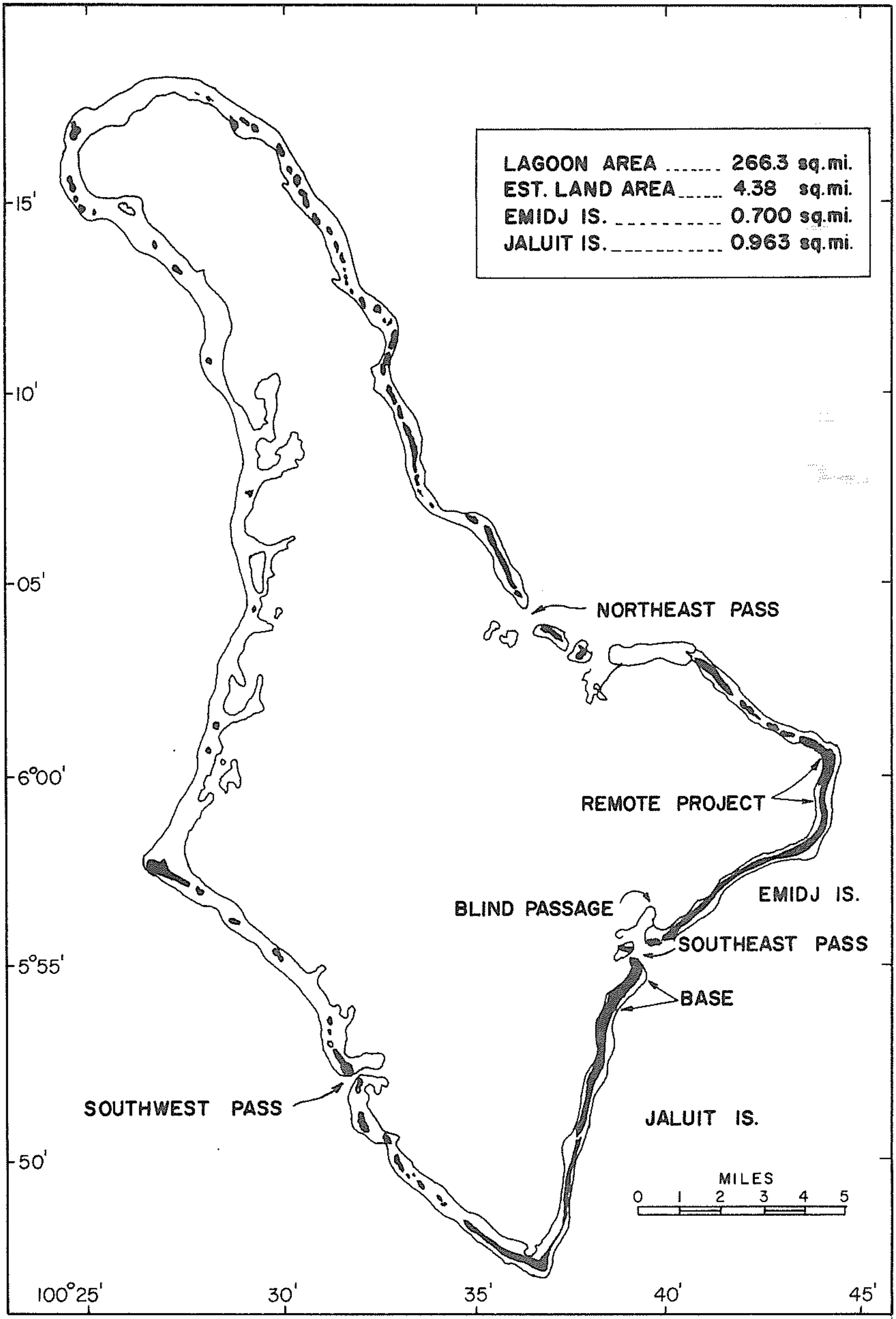

Figure 14. Jaluit Atoll.

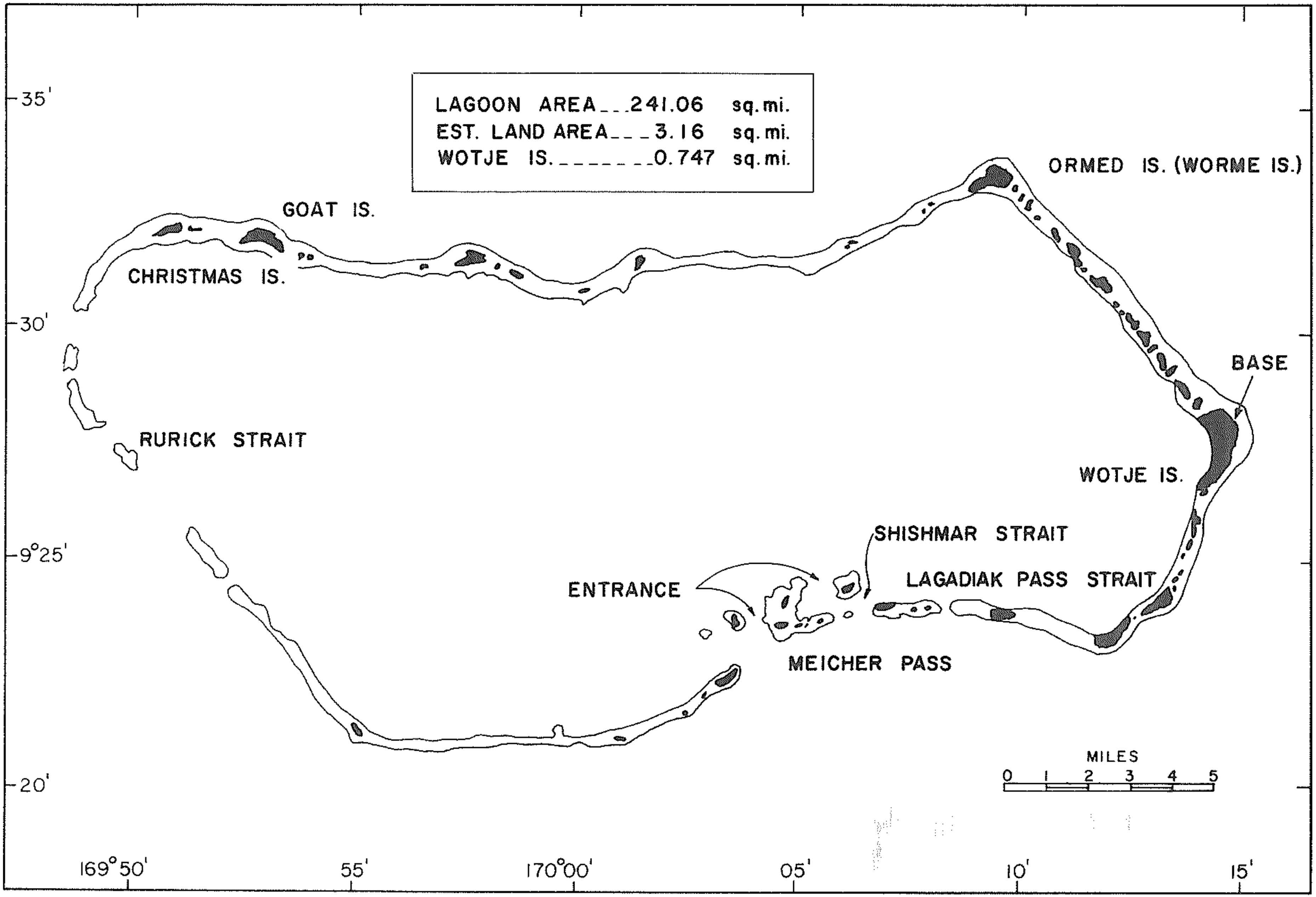

Figure 15. Wotje Atoll.

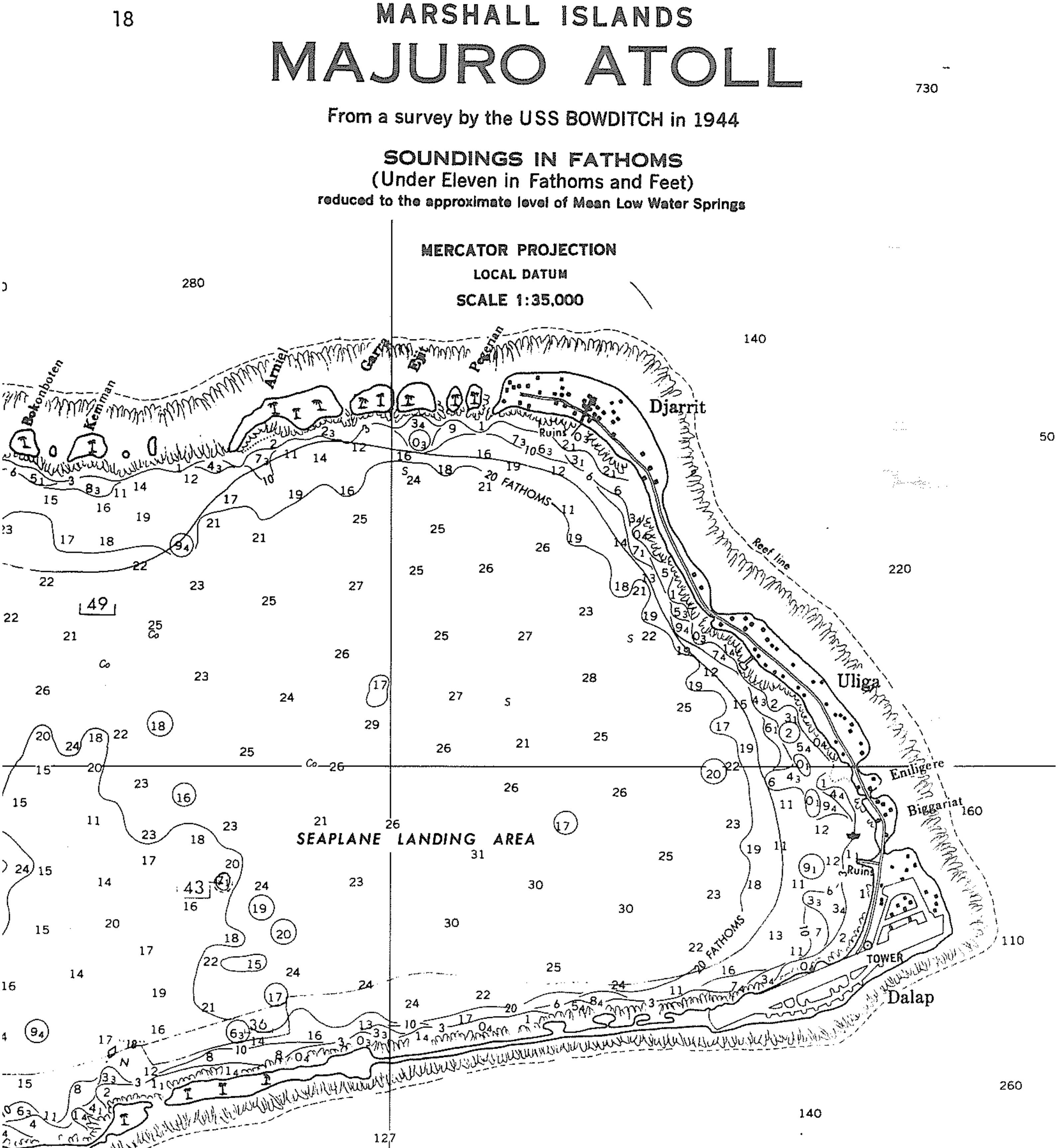

Figure 16. 1:35,000 Scale Map of a Portion of the Majuro Atoll.

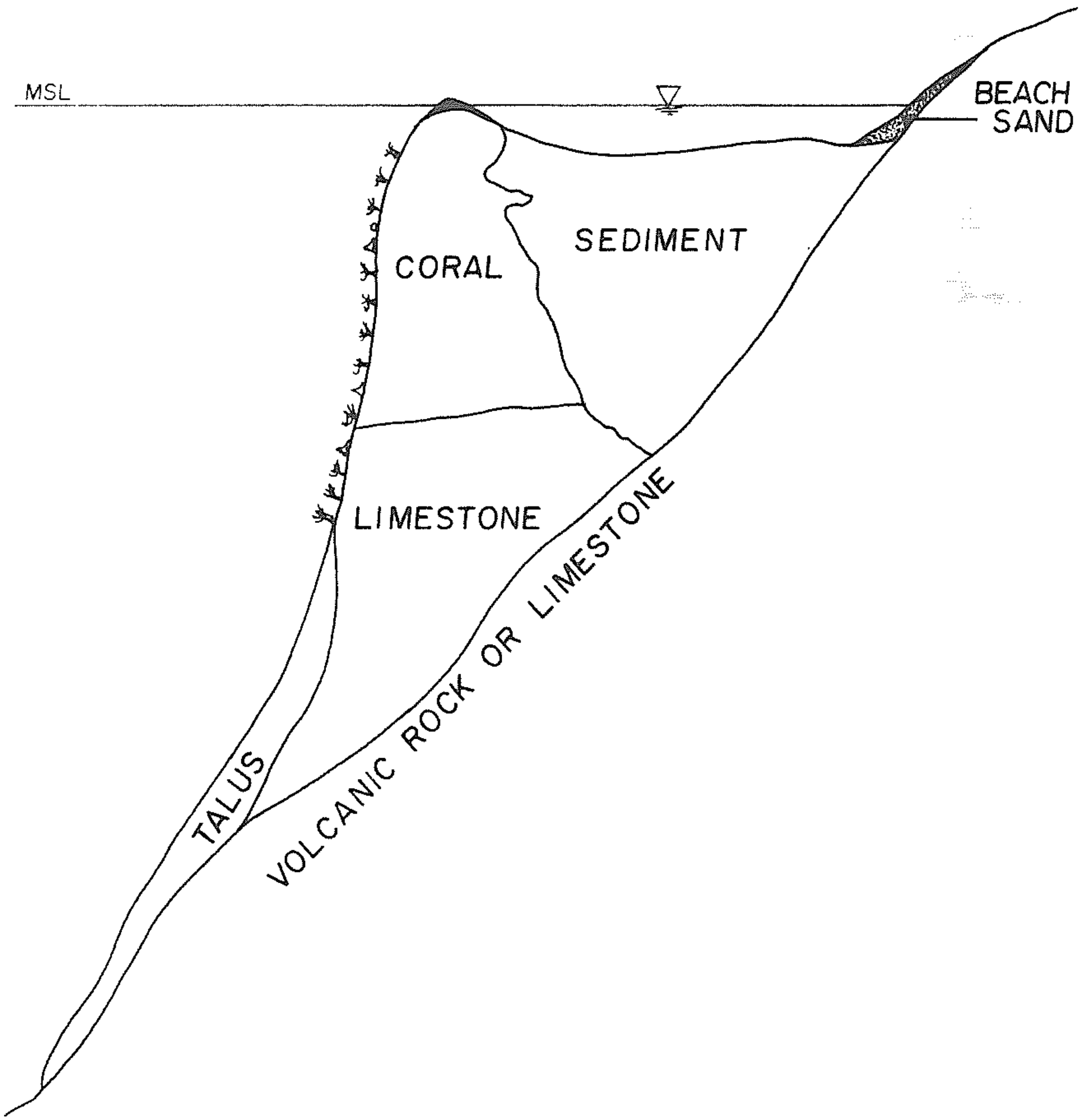

Figure 17. Fringing Reef Profile.

WORLD-WIDE DISTRIBUTION

Figure 18 illustrates the world-wide coverage of the coral-growing belt. Indeed coral reefs are scattered over 68,000,000 square miles of area and thus fringing reefs, barrier reefs, and 330 atolls are found, according to Wells, wherever a suitable substratum lies within the lighted waters of the tropics beyond the influence of continental sediments and away from the cool upwellings of the sea in the eastern parts of the ocean basins[12].

Wells calls the portion of the belt from the Red Sea to Panama the Indo-Pacific area and states that the coral reef communities in the area are remarkably constant in composition and species. The number of species, from protozoans to fish, living in any reef tract has never been determined but is estimated at 3,000 in areas such as the Great Barrier Reef of Australia, the Celebes, Palau or the Marshall Islands. Beyond the dotted line in the figure, faunal attenuation occurs rapidly. As a result reef development decreases with the attenuation of the reef community. The rest of the belt is called the tropical Atlantic area and while sea temperatures are about the same as in the Indo-Pacific area, comparable reefs are only developed (and then only weakly) in the Caribbean, West Indies, parts of southern Florida, the Bahamas, Bermuda, Brazil and the Gulf of Guinea. Elsewhere influxes of fresh water and sediment from adjacent lands greatly reduce possibilities of coral growth. The number of reef coral fauna is appreciably less than in the Indo-Pacific area and reef structures are almost always of the fringing type.

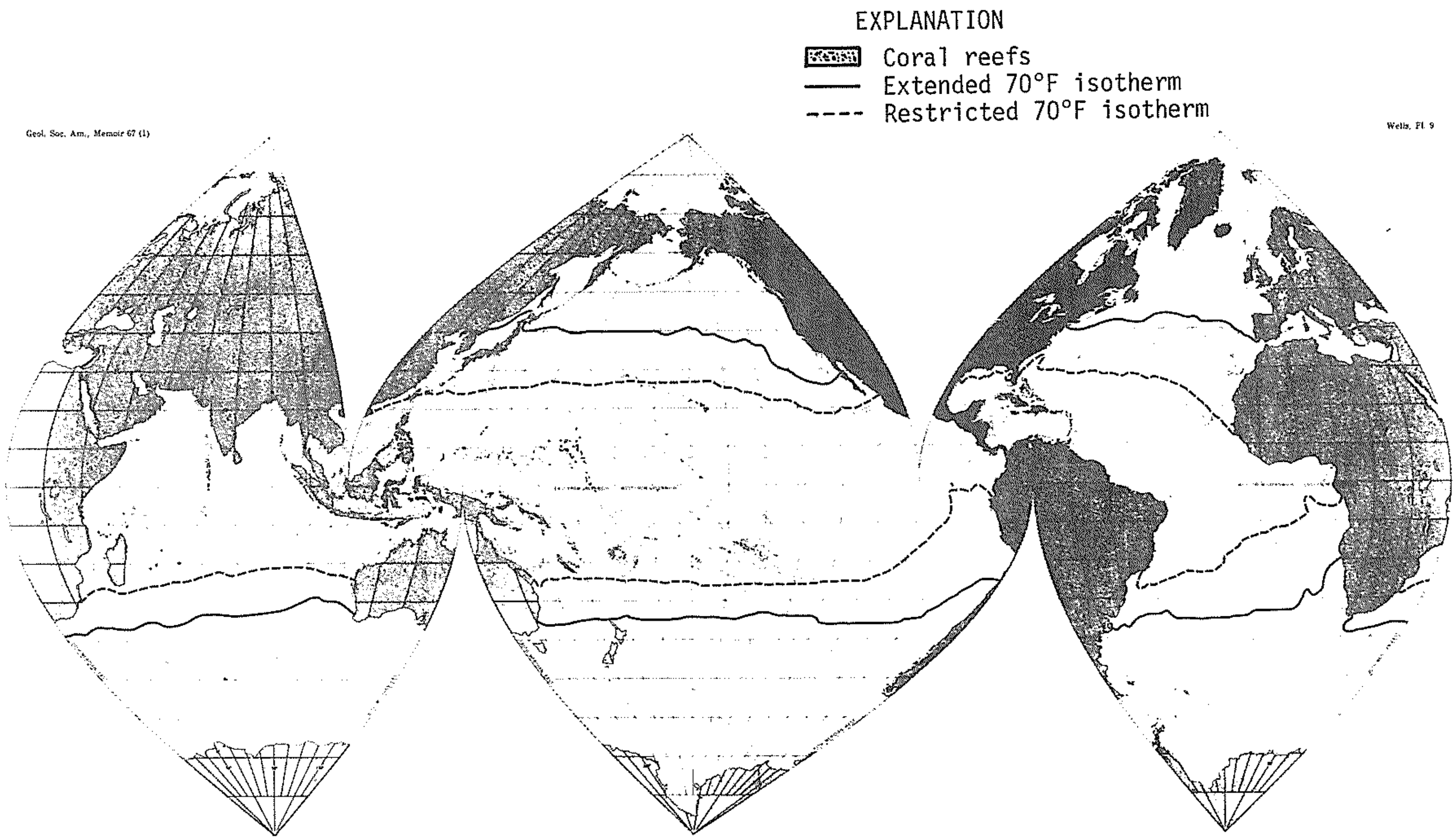

Figure 18. Distribution of Reefs and
Relation to Controlling Sea Surface Temperatures.
[Reproduced by permission of the Geological Society of America, Memoir 67 (1).]

ENGINEERING PROPERTIES

Engineering data on the suitability of different grades of coral for construction purposes are given in the following references. Unfortunately, the terminology for describing different or equivalent grades of coral is not uniform among references (Figure 19). Key points from each reference are listed below.

Coral

Unit Weight - 50-165 pcf

Hardness (Mohs scale) - 3

Absorption - high

Soundness - less than 18%

- less than 15% (fine)

Coral limestone

Grade L-1

Specific Gravity - greater than 2.2

Hardness - hard

Compressive Strength (Unconfined) - greater than 700 psi

Grade L-2

Specific Gravity - 2.0

Compressive Strength - greater than 300 psi

Coral Limestone Breccia

Grades LB-1 and LB-2 - Equivalent to

Coral Limestone grades L-1 and L-2, respectively.

Color - white to tan and mottled brown

Particle size - 0.1 inch to eight inches

Particulate Nature - cemented angular fragments

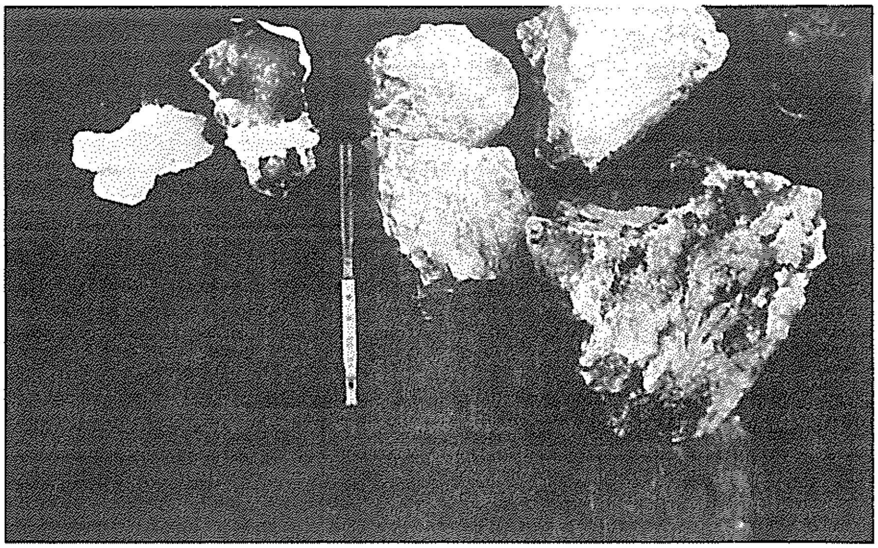

Figure 19. Coral Fragments. From left: Coral, dredged by dragline.

Calcareous sandstone, dredged from lagoon by dragline.

Coral, blasted from lagoon side of Majuro reef.

Coral, blasted from ocean and windward side of Majuro reef.

Grade LB-3

Color - white to light tan

Particulate Nature - Soft-cementing matrix

<u>Calcareous Sandstone</u>

Color - white to tan and red

Particle Size - 0.4 mm to 2 mm

Particulate Nature - cemented fragments comprising sand, coral and shell

Hardness - wide variance (in resistance to excavation)

Grades CS-1 and CS-2 - equivalent to

Coral Limestone grades L-1 and L-2, respectively.

<u>Unconsolidated Bioclastic Sediments</u>

Color - Light gray with traces of brown, red, green, and black

Particle Size (Unified Soil Classification System) - SM, SP, GM, GP*

Compressive Strength (Unconfined) - 1737-2247 psi (obtained on cores from a reef quarry on Kwajalein).

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* Descriptions of soil classifications are given in the Appendix (page 50)

Stearns on Coral in General[11]

Coral deposits, whether from reef, beach or lagoon, and whether old or young, have three common properties: marine origin, high lime content and white or cream color. The best coral for use in concrete is the heavy nodular coral in which the center is crystalline calcite (sp. gr. 2.7). This coral works best after crushing and screening and is known as windward atoll beach rock. The "live coral" of the Seabees is a combination of coral, sand, coralline algae, shells foraminifera, organic material and limy mud. The cementation effect is still being studied but may be due to the presence of fine limy material of silt size and decomposing marine organic material which releases organic acids which react with the lime. However, organic material is not necessary for cementation, which is the case in Guam. There the ocean salts and carbon dioxide from rainfall and ocean spray yield conglomerates after several cycles of alternate wetting and drying. Precipitation of lime may also be a factor as well as the fact that salts deliquesce. In general, submerged coral deposits containing a good percentage of limy muds are most economical to handle. These "set up" most rapidly, particularly when aided by saltwater sprinkling.

Legget on Coral[8]

Loose Particle Unit Weight (pcf)

Coral - 70-110

Finger Coral - 60-80

Coral possesses a "setting up" quality.

Perry on Coral[10]

Wet (fresh) coral piled neatly, spread quickly, compacted well and set quickly. Fears that dead coral is unsuitable for fill are unjustified. It sets slower and yields a less durable surface. Lack of sufficient fines was the most common problem when using coral for building roads and airstrips.

There are considerable differences in density among the several kinds of coral although most have a specific gravity of around 2.0. Coral which has a specific gravity of 2.5 to 3.0 is really limestone. A cubic foot of seawater will deposit an eighth of an inch of solids, which may have some cementing value. The cocino blocks which the Spanish carved and set some 400 years ago in Florida are now so cemented by seawater that they appear as one solid piece.

Field compaction ranged from 94.5 to 112.9 percent of Standard Proctor maximum density. Average optimum moisture content was 20.2% but some coral can absorb up to 28% by weight without expanding to form a plastic mass.

<u>Krynine and Judd on American Coral</u>[7]

Specific Gravity (apparent) - 2.66

Porosity - 1.06%

Absorption - 0.41%

Unit Weight (dry) - 166.2 pcf

Compressive Strength - less than 5000 psi, similar to tuff, chalk, very porous sandstone and siltstone.

<u>Limestone Reef Breccia</u>

Compressive strength - 860 to 4960 psi

<u>Duke on Guam Coral</u>[5]

Reef Coral

Specific Gravity - 1.7 to 2.2

Absorption - 5% to 20%

Soil Class (Public Roads Administration, PRA,)-A-2

Lagoon Coral

Specific Gravity - 1.8 to 2.4

Absorption - 5% to 20%

Soil Class (PRA) - A-3

Coral Sand

Specific Gravity - 2.6

Absorption - 1% to 3%

<u>Cascajo</u> (Spanish for gravel and Guamanian for talus sediments)

Grade A

Specific Gravity - 2.3 to 2.6

Absorption - 3%

Soil Class (PRA) - A-3

Angle of Internal Friction (ϕ) - 28 degrees

Cohesion - 1300 psi

Grade B

Specific Gravity - 2.3 to 2.5

Absorption - 5% to 10%

Soil Class (PRA) - A-1

Angle of internal friction - 18 degrees

Cohesion - 1000 psi

Grade C

Specific Gravity- 2.2 to 2.4

Absorption - 7% to 15%

Soil Class (PRA) - A-6 or A-7

Angle of internal friction - 10 degrees

Cohesion - 200 psi

Coral and Cascajo Hydraulic Dredge Fill

Angle of internal friction - 35 degrees

Cohesion - 0

No evidence of cascajo becoming harder or of "setting up" after addition of water or with time.

Dalrymple on Guam Coral[2]

Pit Coral (best for base courses)

Plasticity Index (seawater) - 4.0

Plasticity Index (freshwater) - 1.5

California Bearing Ratio (CBR) values - higher with fresh water.

Quarry Rock

CBR values - higher with seawater

Seawater causes solidification ("set up").

Sample designs using CBR and Asphalt Institute (AI) methods for measuring thickness design:

40,000 lbs taxiway

37 inches of coral materials - CBR

30 inches - AI

12,000 lbs highway

12 inches - CBR

11.3 inches - AI

150,000 lbs runway

50 inches - CBR

51 inches - AI

U.S. Navy, Civil Engineering Laboratory[17]

Eniwetok Reef Coral

Unit Weight - 84 pcf

Specific Gravity - 2.6

Absorption - 2.2%

Kwajalein Lagoon Coral

Unit Weight - 69 pcf

Specific Gravity - 2.2

Absorption - 10.7%

Use rich mixtures for low permeability concrete. Use eight bags of cement per cubic yard of concrete and allow 6 weeks for curing of low permeability concrete. To prevent corrosion of reinforcing steel, paint the windward side of concrete structures.

A small amount of seawater salts may be beneficial to concrete if rigid controls are exercised. At a mixing water salinity of 25 gm/kg, strength is improved, water vapor transmission is minimized, and in the case of one low-strength concrete investigation, corrosion of mild steel was negligible.

Narver on Eniwetok Coral Concrete[9]

Oceanside Coral

Specific Gravity - 2.62 to 2.65

Absorption - 1.0% to 2.18%

Use the aggregate with highest specific gravity and lowest absorption for concrete.

Eniwetok Coral Sands Gradation:

	% pass No. 200	100	50	30	16	8	4
Beach sands	0	0	4	30	66	90	95
	0	0	2	11	31	81	93
	0	2	10	50	89	96	98
	0	0	8	90	98	99	
Pit-run sand	0	0	1	23	67	96	
	0	1	11	91	99		
	1	2	22	44	59	75	83
Quarry-run sand - mix	6	10	20	38	54	84	100
- min	2	4	15	42	64	84	100

Nichols, Flint and Saplis on Military Geology of Okinawa[15]

Coralline Rubble

Specific Gravity - 2.54 to 2.62

Absorption - 8.4% to 11.23%

Abrasion (500 rev.) - 44.18%

Soundness (5 cycles) - 36.47% to 22.15%

Quarry Limestone

Specific Gravity - 2.58 to 2.68

Absorption - 1.63% to 3.09%

Abrasion - 34.09%

Soundness - 1.07% to 11.59%

Residual Clay

CBR - 10

Dempsey on Bermuda Coral and Saltwater as Concrete Materials[4]

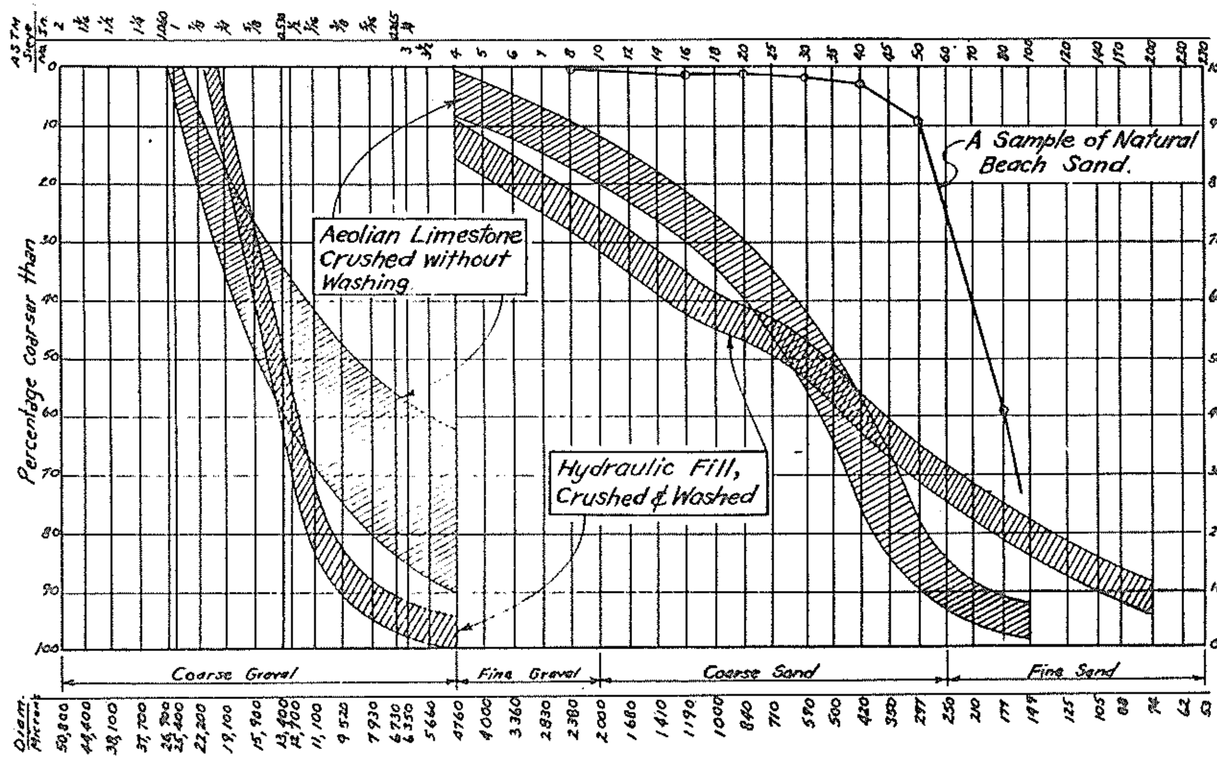
In Bermuda most aggregate is from coral or aeoline limestone. Aggregate dredged from the sea was rough in surface texture and irregular in shape. It contained a high percentage of long and thin particles. Approximately 60% were coral fragments with 10-20% shell fragments. With the sand the mixture was a durable one. Specific gravity of the coarse fragments was 2.45 while that of the sand was 2.53. Figure 20 shows gradation characteristics. Concrete of coral and saltwater resulted in 7-day strength obtained in 3 days.

In 1927 the Navy published data on an experiment with 1:2 and 1:3 mortars made with salt water, and stored for 7 years in wooden boxes and then for 16 and 2/3 years in tidewater. The general condition of the samples was excellent with some erosion at the corners. The reinforcing steel, which had an inch of concrete cover, was rusted in only one case and in no case was the steel pitted.

When saltwater concrete hardens, sodium chloride and magnesium sulfate are left behind and are inert except in the presence of air or moisture. In porous concrete, air and water can put salts back into solution which then attacks both cement and steel. If two different metals are present the solution becomes an electrolyte and accelerated corrosion proceeds.

Maximum density concrete was obtained by adding 8-12% fine sand (passing No. 200 mesh), which cut absorption from 13% to 8% by weight. Using one-inch maximum aggregate, 39 gallons per cubic yard yielded a 3-inch slump. Using seawater rather than fresh water resulted in a significant stiffening of the mix. Twenty-eight-day strength averaged 3500 psi using 5.85 sacks of cement per cubic yard.

To summarize these data, the following statements appear to be re-



—Gradation curves for aeolian limestone and hydraulic fill materials. Width of bands show deviation from average for different sizes

Figure 20. Gradation Curves for Bermuda Coral. (After Dempsey, ACI, 1951.)

presentative:

1. Coral is a term which covers a wide variety of limestone rock, lagoon talus sediments, bluff deposits, and growing plants and materials. Its properties vary widely and engineering tests should be carried out before it is used for construction purposes.

2. On an atoll, usable materials are:

   a. Windward Reef Coral

      Dry unit weight - 70-110 pcf (loose)

      Specific Gravity - 2.5 to 2.7

      Absorption - 1% to 4%

      Soundness - 1% to 10%

      Compressive Strength (Unconfined) - 1700-2250 psi

      Abrasion - 34%

   b. Lagoon Coral

      Dry unit weight (loose, rodded) - 60-80 pcf

      Specific Gravity - 1.8 to 2.4

      Absorption - 5% to 20%

      Soundness - 18% to 36%

      Compressive Strength (Unconfined) - 300-700 psi

      Abrasion - 44%

   c. Lagoon Sediments

      Dry Unit Weight - 50-165 pcf

      Specific Gravity - 1.8 to 2.6

      Absorption - 1% to 20%

      Angle of internal friction - 35 degrees

Cohesion - 0

Average field compaction - 102.6% Standard Proctor

Average optimum moisture content - 20.2%

d. Beach Sand

Nearly uniformly graded

Specific Gravity - 2.3 to 2.53

Absorption - 1% to 3%

3. On a volcanic island with a barrier or fringing reef, usable materials are:

a. Wind reef coral - same properties as for an atoll

b. Lagoon or leeward coral - same as for an atoll

c. Lagoon sediments - same as for an atoll

d. Beach sand - same properties as for an atoll

e. Pit, bluff coral, Cascajo (weathered coral, clay and loam)

Specific Gravity - 2.2 to 2.6

Absorption - 3% to 15%

Abrasion - more than 40%

Angle of Internal Friction - 10-28 degrees

Cohesion - 200-1300 psi

f. Limestone

Specific Gravity - 2.6 to 2.8

Absorption - 1.6% to 3%

Abrasion - 34%

Soundness - 1% to 10%

Compressive Strength (Unconfined) - 5000-10,000 psi

4. The hardest coral is found on the reef on the windward or ocean side. It is best for concrete. Pit coral is good for base course work. Dredged lagoon sediments make good fill and temporary base or surface course material. In certain environments this material will stabilize and harden after applications of seawater or fresh water and periods of alternate wetting and drying.
5. It is very risky to generalize about the properties of coral as there are so many forms and combinations. Proper soil and rock mechanics tests should be carried out before designing foundations in or on coral. This summarized data should be used only as a guide to what conditions <u>might</u> be found.
6. Significant quantities of fines will probably need to be added to coral aggregate to get low permeability concrete. It is indeed possible to make good concrete out of coral aggregate and seawater. If proper attention is given to mix design, reinforcing steel placement and concrete placement, saltwater coral concrete will be a low permeability concrete which will not corrode the steel.

EXCAVATION DATA

The softer forms of coral can be moved economically by hydraulic dredge. As shown in Figures 21 through 25, it was common practice in Okinawa to move channel and offshore sediments by pipeline dredge. In Figures 21 through 25 a fishing boat channel and inlet are being widened, while in Figures 27 and 28 a land bridge is being formed between two islands. The small hydraulic dredge shown in Figures 21 through 25 is of Japanese design, having a 730 hp engine and producing 40 cubic yards of fill per hour. Figure 26 shows a completed causeway.

The harder reef coral requires blasting. A reef may be only a hundred feet wide from ocean to lagoon. Perhaps the quarter of this distance closest to the lagoon will be much softer and some of this may be a ledge perhaps 8 feet thick and underlain by sand. In the Marshall Islands, drilling one-inch holes for dynamite proceeds easily at about one foot a minute. In the Kwajalein lagoon, prestressed and H piles were driven to necessary bearing of 13 to 15 feet through coral easily. According to Narver, wooden piles can be driven through the lagoon shelf.

According to the Blaster's Handbook, using the so-called Doby or surface method, 50-pound boxes to 60 to 80 percent gelatin dynamite placed 8 to 10 feet apart on the bottom will yield 3 to 4 feet of depth per blast[13]. According to Narver, reef quarrying on Eniwetok was accomplished by drilling and blasting. Two-inch holes on 3-foot centers were drilled 4 to 5 feet deep and charged with two 60 percent 1.5-inch by 12-inch sticks of dynamite[14].

There have been recent attempts to cut through a coral reef in Diego

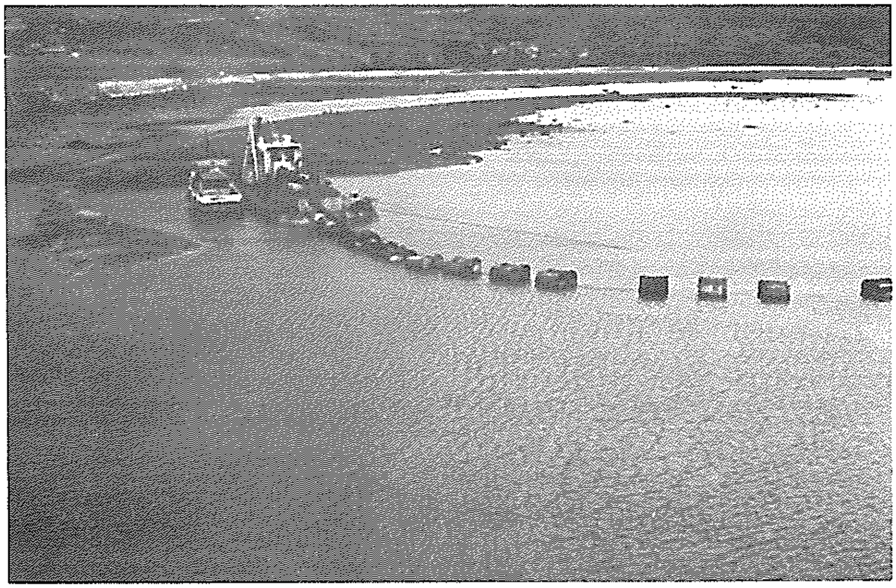


Figure 21. Small Hydraulic Dredge Pumping Sediment at O-Shima, Eastern Side of Okinawa.

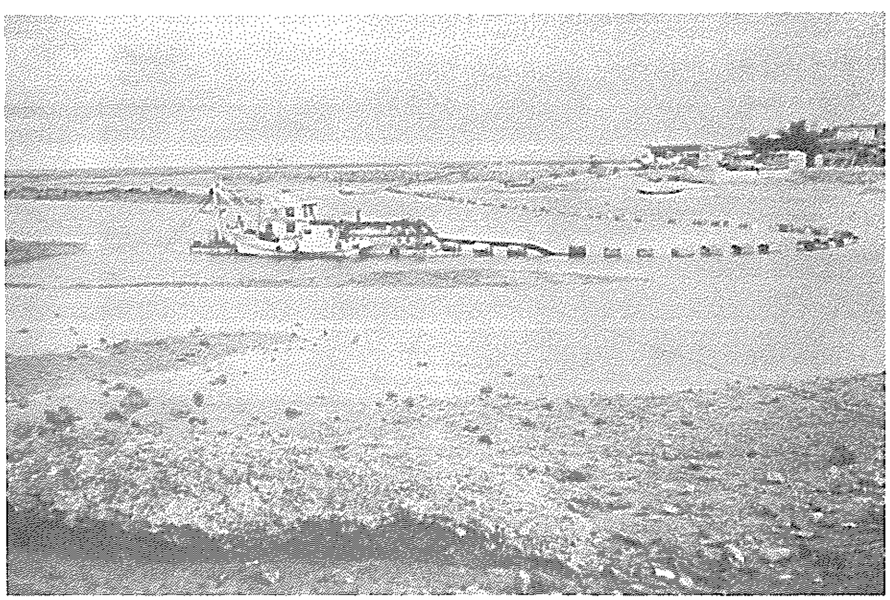


Figure 22. Small Cutterhead Dredge—Powered by 750 hp Engine—Has 40 yd^3/hr Output.

Figure 23. Dike of Coralline Limestone Contains Dredgings.

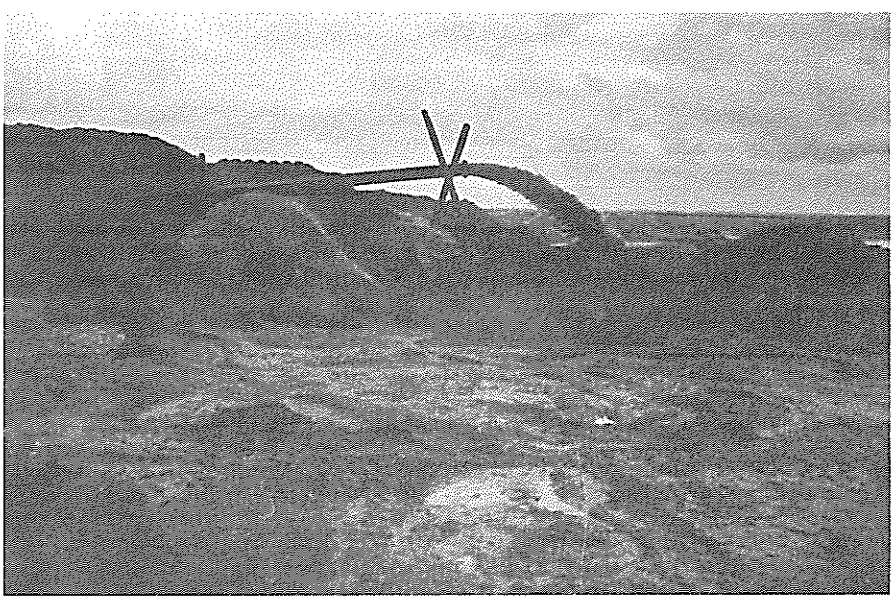


Figure 24. Channel Sediments.

Figure 25. Area to be Filled.

Figure 26. Causeway of Coralline Limestone, Okinawa.

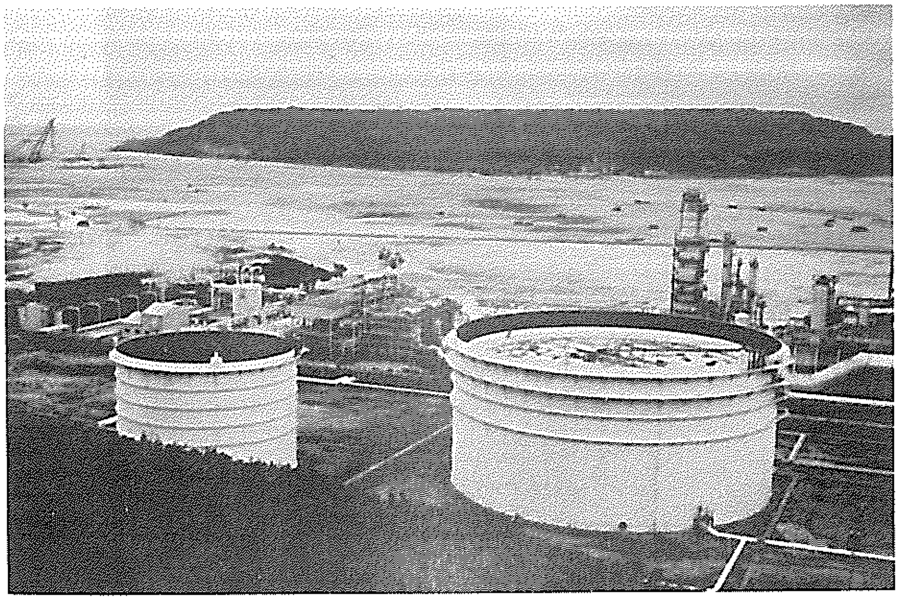


Figure 27. Hydraulic Fill, Okinawa.

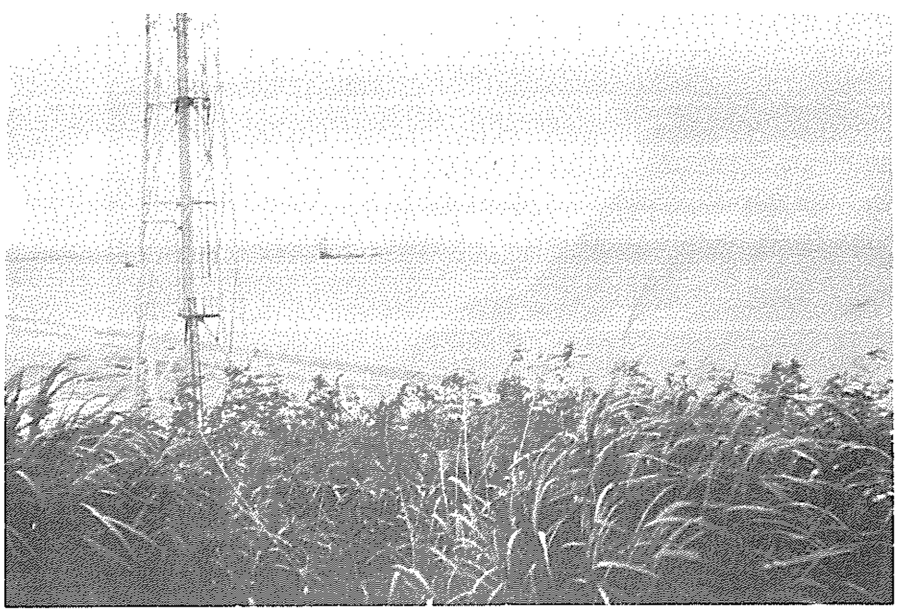


Figure 28. One of Several Large Hydraulic Dredges Which Accomplished the Above Fill.

Garcia Atoll in the center of the Indian Ocean by hydraulic dredge. The Taiwan contractor has run into difficulty cutting the reef with the cutter-head and is considering going to blasting.

According to Legget, there have been several instances where hard solid rock has been moved by hydraulic dredge. On the Lake Okeechobee waterway project, layers of marl and limestone had to be broken initially by drilling and blasting but the material was handled hydraulically from that point on. In the harbor of St. Helier, Jersey, a 22,000-pound ram was used to break up syenite granite and diorite. At Sunderland, England, over 100,000 cubic yards of loosely bedded limestone was excavated to a depth of 44 feet without blasting or use of a rock breaker. A large dipper dredge accomplished the task[15].

The senior author has personally seen a contractor excavate shale by getting a larger dragline bucket and dropping it from a considerable height to break up the material so that it could be handled. This procedure was used at Rocky River, Ohio, near Cleveland, to deepen a small-boat channel and harbor. Blasting could scarcely have been tolerated.

In the Solomon Islands, in World War II, coral was blasted and excavated in depths up to 18 feet by a most unusual method. A pile-driven barge drove pipes into the coral. Dynamite was placed in the pipes and detonated, shattering the coral to the point that a clamshell dredge could remove it[16].

According to Perry, another expedient method was to fix 50- to 100-pound charges to a cable which was laid out in the area to be dredged. The average shot yielded a fractured area about 30 feet in diameter and 3 to 4 feet deep. He also reported that when dredging lagoon sediment with a hydraulic dredge, it was necessary to move the exit end of the pipe frequently in order to prevent segregation of material and muck pits[17]. Additional examples of dredging coral are shown in Figures 29-32.

If concrete blocks of rip-rap are intended to prevent erosion of hydraulic fill, or other concrete structures are needed to protect the results of the coral excavation, it should be noted that concrete made with coral aggregate and seawater is sufficient. Using seawater and coral aggregate it is possible to make 2000 psi concrete which is 17% stronger during the first month than an identical mix which used fresh water. At the end of 90 days, however, the freshwater concrete had 6% higher strength.

There is now controversy over whether saltwater and sea aggregate cause corrosion of reinforcing steel in concrete over a period of 50 years. Previous Navy studies have shown otherwise and the Eniwetok study included demolition of 5- to 7-year-old World War II concrete structures. In most cases the reinforcing steel was clean but in a few cases it was corroded. The corrosion was attributed to faulty design and placement, porosity and external moisture. Dempsey's report of no corrosion after 24 years is similar to what was found in 30-year-old Japanese structures.

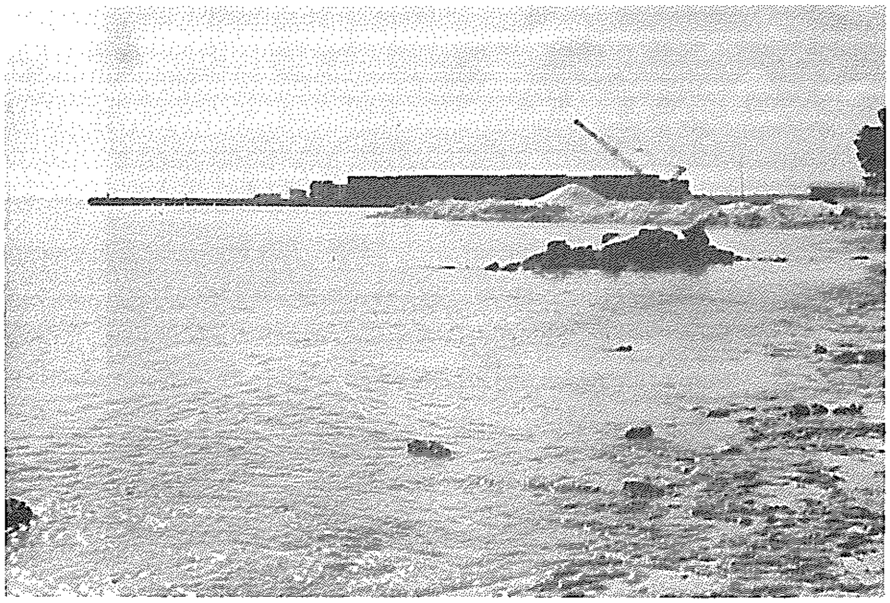


Figure 29. Majuro Lagoon, Marshall Islands.

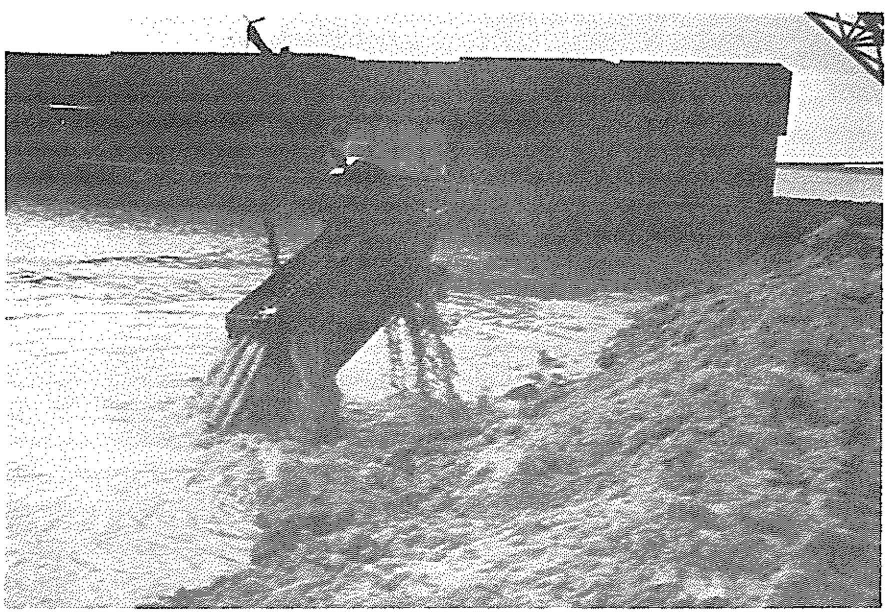


Figure 30. Dredging Lagoon Sediments by Dragline.

Figure 31. New Land by Hydraulic Fill.
Nakakusuku Bay, Okinawa.

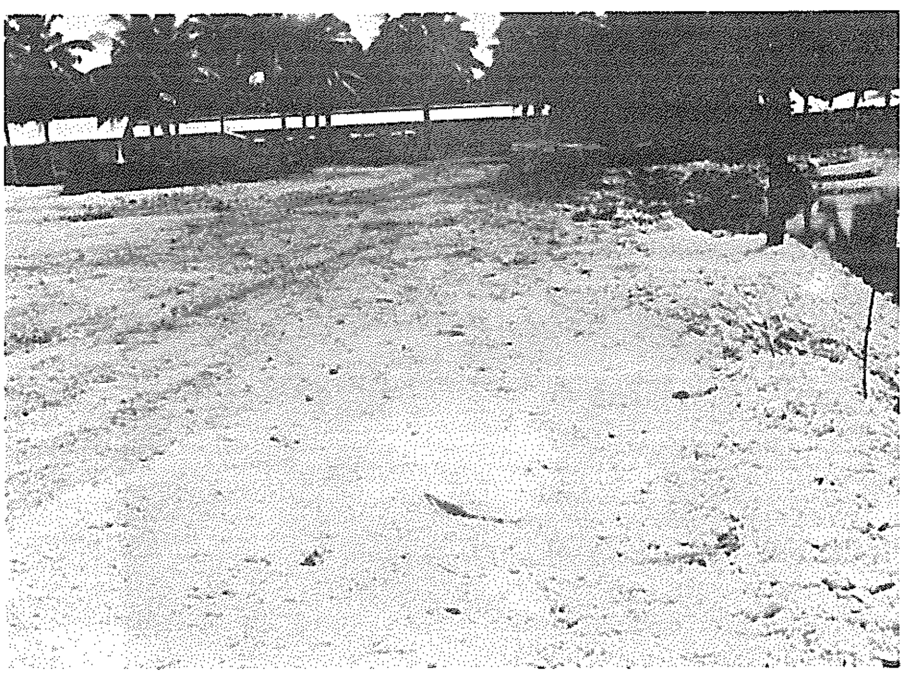


Figure 32. Coral Causeway, Jaluit Atoll, Marshall Islands.

CORAL DREDGING AND ITS USE FOR CONSTRUCTION

From reported data as well as from data obtained in the course of the present study it appears that selective dredging of coral is both possible and desirable.

Hydraulic dredging seems to be the most practical method of deepening portions of lagoons for anchorages. It also is probably the most economical method of excavating lagoon sediments for creating more land or for other construction purposes.

When attempting to cut through the entire reef to create a new pass or to deepen an existing pass, at some point near halfway, a hydraulic dredge will need an assist from a large dragline, rock breaker, or from blasting. This decision will depend on the availability of equipment, the economics of the situation, and how many cutterheads the contractor is willing to expend.

Blasting underwater is receiving more criticism of late, even in remote Micronesia, by environmentalists and others. Opposition to dredging is usually most vocal against open-water dumping rather than excavation for a reasonable purpose. It seems that dredging in coral would be accepted more readily than blasting.

In the next twenty-five years, with the shift in emphasis toward sea resources, Micronesia will almost certainly undergo a period of significant development which will include extensive harbor facilities. The vessels which now operate in Micronesia seldom draw over nine feet of water, with the newest island connector rated at 15 feet. But the trend is apparent and many islands and atolls in that part of the world will perhaps suddenly need deepwater docking facilities. Coral is the only plentiful construction material available locally and various forms of dredging will be necessary to extract it.

Majuro, the district capital of the Marshalls, is a unique atoll, since it has only one natural pass into the lagoon. An attempt at opening a second pass through the reef was made to allow small fishing boats to get out to sea more easily. In this manner the lagoon will get better flushing action during tidal fluctuations. The Doby method of detonating cases of TNT on the reef surface under two or three feet of water did not give smashing results and seemed quite expensive. The use of linearly-shaped charges or drilling and blasting would be much more economical.

Research is being conducted on sophisticated excavators which employ explosive bucket teeth and high-intensity flame to carve out rock. Since even the hardest coral is relatively soft, compared to granite, maybe a large corundum saw could be used in conjunction with a little blasting to yield breakwater stone. The July 74 issue of National Geographic reports that a rock is cut out with torches in a Vermont granite quarry.

The matter of coral concrete is still under debate. Investigators listed in the reference section of this paper conclude that coral concrete, even that made with seawater, is perfectly sound and even advantageous in some cases. Recent building failures (50 years after construction) in Florida have been attributed to corrosion of reinforcing steel. Suspicion has been cast on sea-borne aggregates as perhaps causing these 50-year failures. Massive concrete structures in Micronesia were built by the Japanese 30 years ago or more. They were built using coral aggregate and fresh or brackish water, and appear to be completely serviceable; but they had been designed to withstand high-explosive bombs and shells. There is no doubt that mild steel exposed to salt air and spray will be completely shredded after ten or fifteen years. When demolished to provide breakwater stone, these Japanese concrete structures did not have much corroded or rusted reinforcing steel. Perhaps the life of structures made of coral concrete and seawater should be limited to about thirty years, unless they are made of low-alkaline cement. Tight mix control would allow for the addition of the proper quantity of fines. Painting the surfaces, especially the seaward sides, to make the concrete less permeable will make corrosion of reinforcing steel less probable. Much more research into the Florida building failures is needed to determine the actual cause of the corrosion.

CONCLUSIONS

1. Coral is a unique natural material found in warm, shallow waters in a wide variety of forms and degrees of hardness. The hardest coral is comparable to soft limestone.
2. Coral has been successfully used as a construction material. It can be used in concrete, as landfill,and as base for roads and airfields.
3. Lagoon coral and sediments can be dredged hydraulically. Oceanside reef coral requires heavy mechanical dredging equipment, or blasting, for excavation. Coral reefs vary sufficiently in character to make core drilling and extensive engineering materials tests a desirable preliminary step to sophisticated construction.

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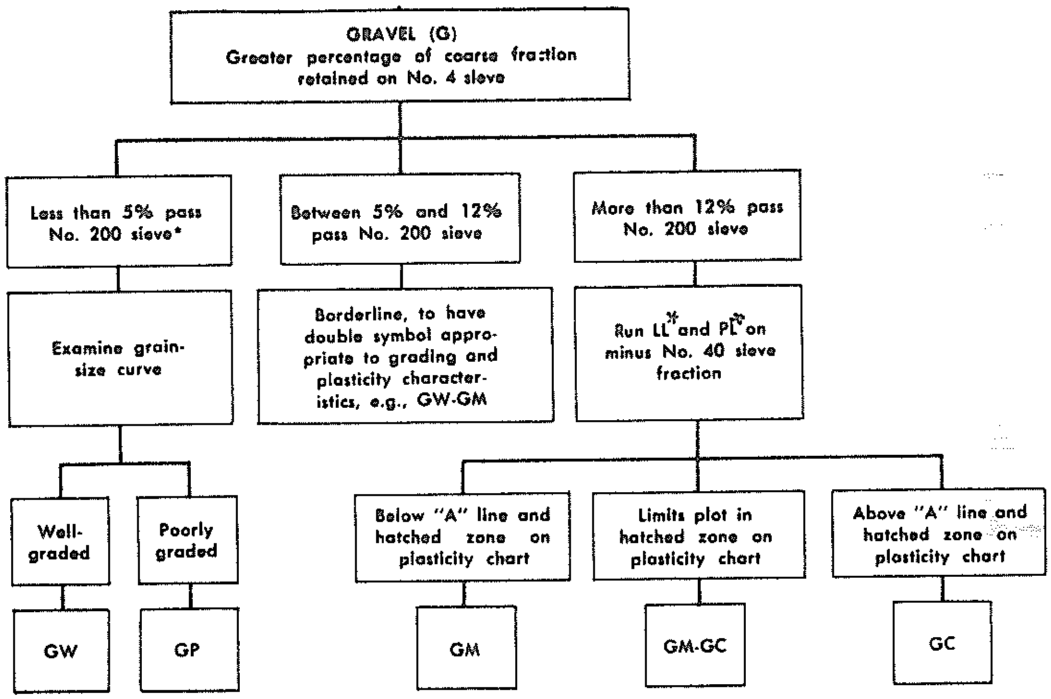
APPENDIX

Soil Classifications



*LL - Liquid Limit
PL - Plastic Limit

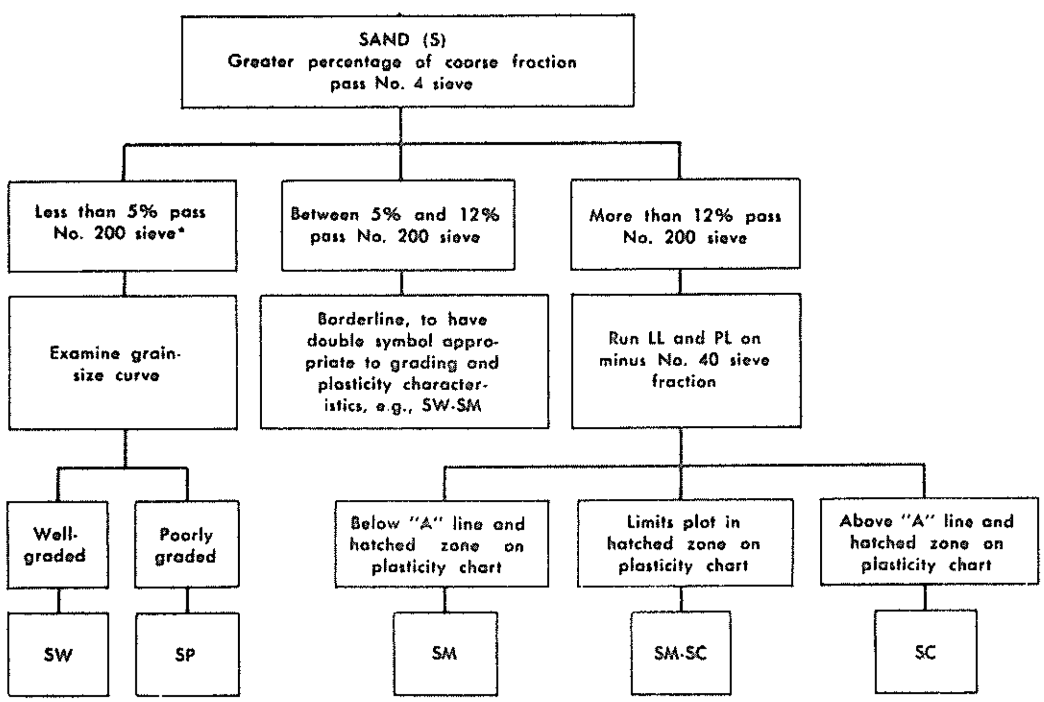
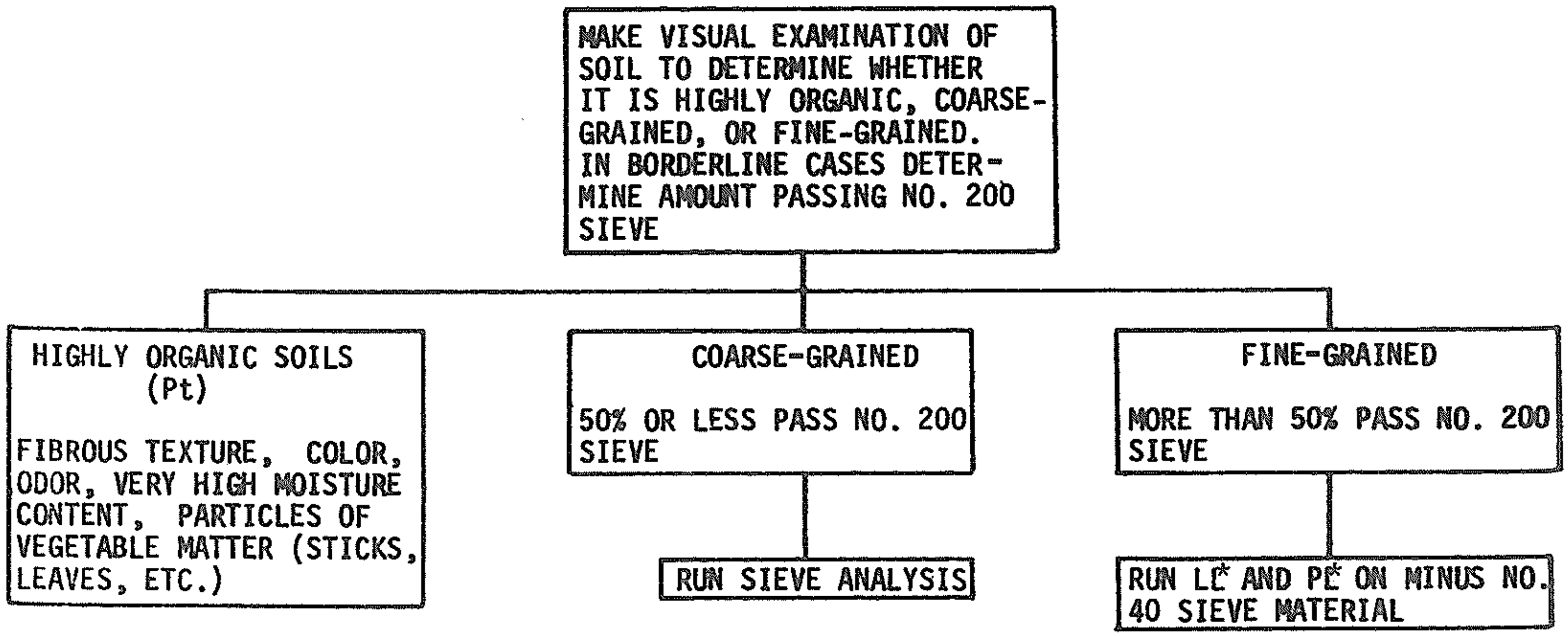


Figure A-1. Coarse-Grained Materials



*LL - Liquid Limit
PL - Plastic Limit

Figure A-2. Auxiliary Laboratory Identification Procedure

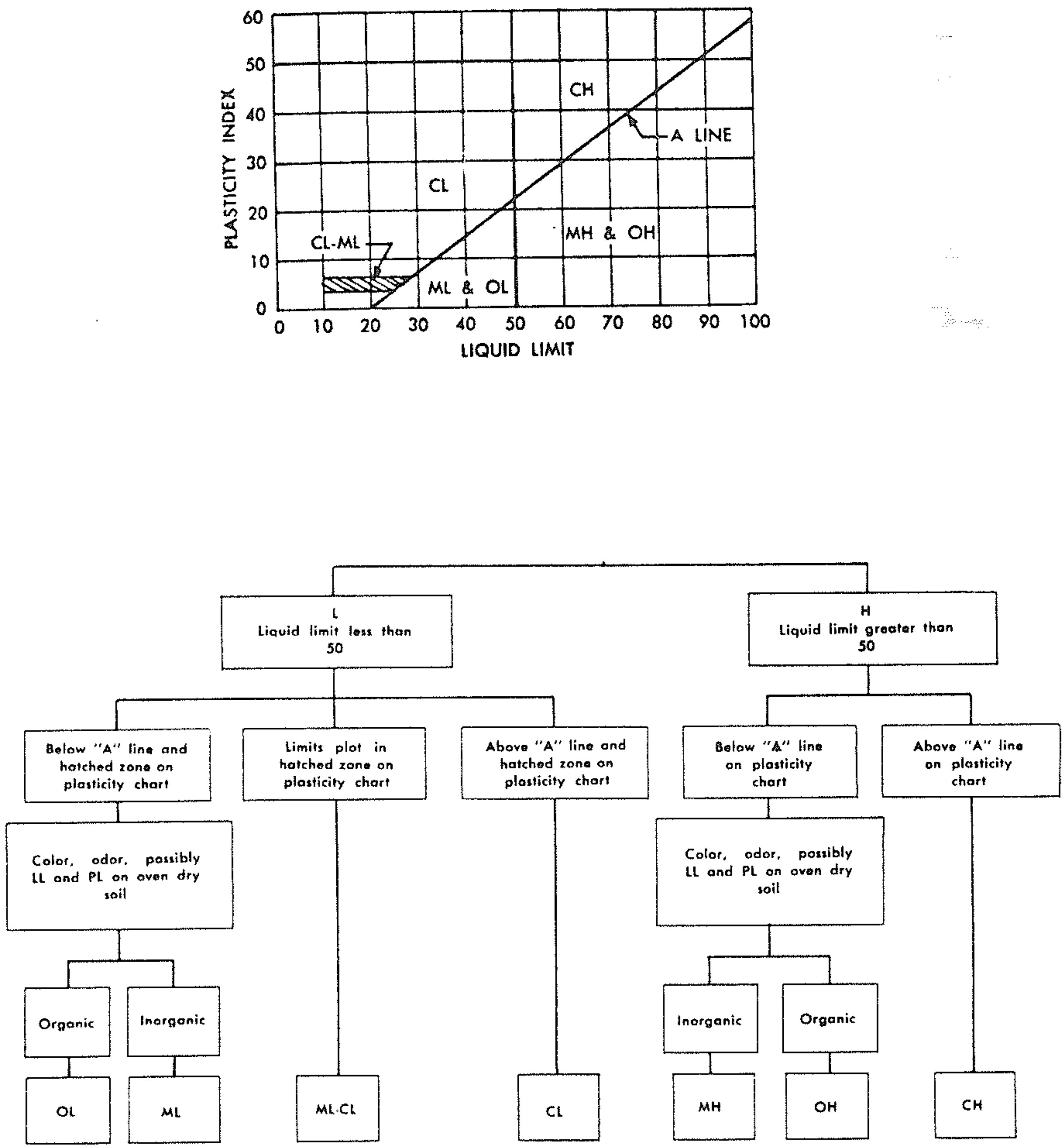


Figure A-3. Fine-Grained Materials